

ADVANCED RELEASE TECHNOLOGIES PROGRAM

Bill Purdy
Naval Research Lab
Washington, DC

Abstract

The objective of the ARTS program was to develop lighter and less expensive spacecraft ordnance and release systems that answer to the requirements of a wide variety of spacecraft applications. These improvements were to be evaluated at the spacecraft system level, as it was determined that there were substantial system-level costs associated with the present ordnance and release subsystems. New, better devices were to be developed, then flight qualified, then integrated into a flight experiment in order to prove the reliability required for their subsequent use on high-reliability spacecraft. The secondary goal of the program was to quantify the system-level benefits of these new subsystems based upon the development program results.

Three non-explosive release mechanisms and one laser-diode-based ordnance system were qualified under the program. The release devices being developed were required to release high preloads because it is easier to scale down a release mechanism than to scale it up. The laser initiator developed was required to be a direct replacement for NASA Standard Initiators, since these are the most common initiator in use presently. The program began in October, 1991, with completion of the flight experiment scheduled for February, 1994. This paper will: 1) provide an overview of the ARTS program, 2) discuss the benefits of using the ARTS components, 3) introduce the new components, 4) compare them with conventional systems and each other, and 5) provide recommendations on how best to implement them.

Program Overview

The ARTS program had two distinct phases: Phase 1) development and evaluation, and Phase 2) qualification and flight experiment production. An industry survey was done to evaluate many components in the early stages of research and development. The three most promising release devices and the most promising laser ordnance system were selected for phase 1 development. The selected devices were then developed to meet the level of reliability needed for flight production. Phase 1 concluded with a thorough test series to measure the devices' performance envelopes. Phase 2 took the phase 1 designs, made any minor modifications desired after the envelope testing, and then built a single lot of flight and qualification hardware. This hardware was then qualified and used to build a flight

experiment. One of the release mechanisms was rejected for phase 2 after phase 1 exposed inadequacies. The integration of the flight experiment required undergoing range safety reviews and interfacing with the host vehicle. This process exposed many issues, for example, living with current limits from the host vehicle. The production of the flight hardware and experiment proved to be very valuable in that it required us to be truly ready for flight. The overall two-phase process resulting in a flight build worked out quite nicely.

The spacecraft system-level benefits take the form of reduced production costs and result from three key factors: 1) reduced safety efforts, 2) reduced weight, and 3) reduced pyroshock environment. Neither the laser ordnance nor the non-explosive release devices is sensitive to Electro-Magnetic Interference (EMI) thus eliminating most of the safety hazards associated with today's pyrotechnically driven spacecraft components. The insensitivity to EMI allows the elimination of heavy shielding from the firing harness design. The bulk of the weight savings, which can add up to as much as 9 kilograms (20 pounds) on a large spacecraft, results from eliminating this shielding. The non-explosive release mechanisms have a pyroshock output of about one fourth of today's pyromechanical release devices. This characteristic allows spacecraft designers to seriously look at eliminating much pyroshock testing since the levels for almost all of its components will follow this 75% reduction.

A detailed cost analysis was performed comparing production and processing costs for a large satellite with conventional systems and the same satellite design using an ARTS-based system. The analysis showed that the ARTS system cost \$1.1 million per satellite and that the conventional system cost \$1.6 million per satellite. The satellite had already been built with conventional systems so its production costs were accurately known. The dominant savings were: 1) elimination of much of the labor required to get safety approvals, 2) the cost of weight to orbit, and 3) the elimination of a vehicle-level pyroshock acceptance test.

Frangibolt¹

The Frangibolt release mechanism, developed by TiNi Alloy Company in San Leandro, California, and the Naval Center for Space Technology, uses the shape-memory alloy, nitinol, to break a notched bolt in tension upon command to effect a release operation (see Figure 1). The nitinol collar is compressed before installation so that when heated, it elongates to its original length, stretching the bolt until it fails in tension at the notch. A pair of 10-ohm etched foil heaters encased in a common silicone jacket

¹ Frangibolt is a registered trademark of the TiNi Alloy Co., San Leandro, CA

molded onto the nitinol actuator operates with a 24 to 36 volt DC supply typical of most spacecraft power systems. The advantages of the Frangibolt are that it is: 1) very simple, with only one moving part; 2) safe to use; 3) very lightweight; and 4) it produces a low pyroshock output. The disadvantage of the Frangibolt is that it takes from 10 to 60 seconds to operate and is incapable of releasing two locations simultaneously. The Frangibolt was discussed extensively in a paper presented at the 1992 Aerospace Mechanisms Symposium.

The Frangibolt is useful for roughly half the release tasks on typical spacecraft. This system is not capable of releasing several joints simultaneously, nor releasing at a specific time within 1 second. The Frangibolt is especially well suited to releasing items such as solar arrays and hinge-mounted deployables. The Frangibolt has been qualified to operate at 24 to 36 volts from -50°C to 50°C. The Frangibolt has been qualified for typical lifetimes of up to 25 releases by operating several of them 50 times.

The development program was focused on verifying the reliability of the Frangibolt over a wide range of supplied power and operating temperatures. The requirements of high watt density and wide voltage range coupled with large actuator deformations resulted in a very challenging heater design. The development also had a heavy emphasis on optimizing the fatigue strength of the bolt while keeping its breaking properties at their desired levels. The final design of the notched bolt was qualified by testing it to 4.5 million fatigue cycles in a bolted joint that was preloaded to 6670 N (1500 lb) and subjected to ± 6670 N (1500 lb) applied load. The development process highlighted the fact that the Frangibolt is sensitive to compliance in the joint it is clamping. We determined that the Frangibolt installation must be procedurally controlled to verify proper joint assembly and that the actuator has been properly compressed. After long consideration of this sensitivity, it was decided to lengthen the actuator for the flight build in order to provide more margin on actuator stroke. The development process for the Frangibolt was successful in showing its reliability and capabilities.

The Frangibolt was used in both the ARTS flight experiment and in releasing the solar arrays on the Deep Space Probe Science Experiment (DSPSE) spacecraft (also known as Clementine 1). The DSPSE spacecraft will be launched in January, 1994. The Frangibolt acceptance testing consists of: 1) measuring the force and elongation to failure of 10% of the lot of notched bolts, and 2) verifying that the force and stroke output of each actuator exceeds the worst-case bolt breaking strength and elongation. This lot testing on the bolts showed the breaking strength variability, defined as

the standard deviation divided by the mean, to be 2% and the elongation variability to be 9%.

It was shown that the Frangibolt needed to be turned off by a switch activated by the solar array release during its implementation into the DSPSE spacecraft. This prevented the Frangibolt heater from being left on too long and overheating. The Frangibolt had to operate over a wide range of voltages and temperatures so its actuation time was expected to range from 10 to 60 seconds which prevented using a timer to turn it off. The DSPSE solar arrays remain closed for 7 days on orbit before they are opened. The arrays get very hot in this time period so the actuator had to be kept cool enough to prevent it from actuating prematurely. This was accomplished by mounting the actuator against an aluminum plate on the spacecraft side of the interface and using a titanium plate on the solar array to block heat from getting to the actuator. This arrangement kept the actuator at 45°C with the array at 100°C and the spacecraft at 25°C. The importance of a good installation procedure with several cross checks was found to be very important during the DSPSE integration.

Fusible Link

The Fusible Link, jointly developed by Boeing Space and Defense Mechanisms Research Department, in Seattle, Washington and the Naval Center for Space Technology, fuses a strap made of nitinol to unlock a preloaded link to perform a release operation (see Figure 2). When a 30 amp (minimum), 3 volt AC current is applied to heat the nitinol fusing element it weakens and breaks within 300 ± 50 milliseconds, unlatching the two jaws which allows the tensioned link to be pulled out of the separable joint. The DC voltage supply of a typical spacecraft is centrally converted to AC and is fed to a 9:1 transformer located on each Fusible Link, which steps the current up to the required level. Nitinol is used as the fusing element for its properties of high strength, high electrical resistivity and excellent corrosion resistance, rather than utilizing its shape memory effect. The advantages of the Fusible Link are: 1) that it is mechanically simple, 2) is safe to use, 3) has a low pyroshock output, and 4) that it is capable of releasing multiple locations simultaneously. The disadvantages are that 1) it requires a power conditioning circuit to create the high current AC, and 2) that it is the largest of the new devices.

The Fusible Link is designed to release one or more loads of up to 6670 N (1500 lb) simultaneously over a temperature range of -50°C to 100°C with voltage supplied to the power converter at 24 to 36 VDC. This design should be scalable to higher and lower loads, with size and power increasing or decreasing accordingly. The Fusible Link's release motion is very simple mechanically with no sliding friction opposing the motion of the jaws or link, which are its only moving parts. There is moderate complexity in the

DC to AC power converter although it is a relatively simple electrical circuit. An extractor must be used to pull the link out of the separation joint quickly and reliably. A Fusible Link can be used for 50 or more releases with no degradation although it requires replacing the fuse after each operation.

The development process included several iterations on both the mechanical and electrical design. The largest hurdle cleared in the design process was developing the AC heating method necessary to open the fuse fast enough to support the simultaneity requirement. At first, we could not make the fuse draw enough current out of the power converter. We discovered that the inductance of the fuse was as large as its resistance and this was preventing the fuse from drawing the large current it needed. This came as quite a surprise to we mechanical engineers who barely understand DC electricity. The solution to this problem was to redesign the fuse such that it could be located adjacent to the transformer to minimize the inductive loop area of this high current portion of the circuit. Several flexure-mounted jaw designs were tried in the interest of simplicity before they were ultimately rejected in favor of a hinged jaw design; the flexure-mounted jaw is shown in Figure 2. The bending of the flexure, coupled with the high tension loads, resulted in excess stress on the flexure. Ultimately, the development process proved the Fusible Link to be very reliable over the wide range of operating conditions required.

The qualification testing operated the Fusible Link at the required temperature extremes with the required supply voltage extremes. The flight experiment had a 5 ampere current limit imposed on it, which turned out to be a tight constraint when operating the Fusible Link at 36 VDC since the Fusible Link also had to draw enough current to fire quickly at 24 VDC. The acceptance testing required for the Fusible Link consists of electrical measurements, then verifying release while monitoring current draw and time to fire for normal performance. The time to fire is proportional to joint preload as well as to the required fuse temperature rise, so consistent preload control on the fuse installation and separation joint preloading is important for maintaining release simultaneity.

Non-Explosive Separation Nut

The Non-Explosive Separation Nut, developed and qualified independently by G&H Technology, Inc. in Camarillo, California, utilizes their previously qualified Non-Explosive Actuators (NEAs) to unlatch a spring-powered separation nut (see Figure 3). Current is passed across the bridgewires of two redundant NEAs releasing them, which in turn unlocks the release housing of the separation nut that is then driven upward by a spring to disengage the thread segments, thus releasing a preloaded bolt. The advantages of this device are that: 1) it operates within 10 to 20 milliseconds, 2) is safe to use, 3) that it produces a low pyroshock. The

disadvantage of the device is that it contains several moving parts and one highly loaded sliding surface.

The Non-Explosive Separation Nut is qualified to release up to 16,000 N (3500 lb) within 20 milliseconds which supports requirements for release of multiple points simultaneously. The device has been qualified from -150°C to 121°C with a 4.5 amp minimum current while at a 20,000 N (4500 lb) preload. The NEA has been separately qualified as a 3.5 amp all-fire device. This development and qualification took place prior to the nut's implementation in the ARTS program. The nut exhibited the same performance, tendencies and sensitivities as standard separation nuts during its integration into ARTS. The Non-Explosive Separation Nut was shown to be a direct replacement for comparable capability pyrotechnic separation nuts. The acceptance testing for the nuts consisted of releasing them with a mechanical, hand-operated replacement for the NEA at one and at two times their nominal preload of 11,100 N. The Non-Explosive Separation Nut design's scalability to larger preloads is unfortunately limited by the sizing of the release spring. It is expected that a 9.5-mm ($3/8$) bolt will be the largest practical size for this basic design. Other designs utilizing NEAs for higher preloads are presently under development.

Laser Ordnance System

The laser ordnance system, jointly developed by Ensign Bickford Aerospace Corporation in Simsbury, Connecticut, and the Naval Center for Space Technology, ignites explosive cartridges using lasers rather than electrically heated bridgewires. A two-watt laser diode fires down a fiber optic harness into an explosive cartridge igniting the explosive mix with light energy. The advantages of this system over electrically ignited ordnance are: 1) that it is much less sensitive to EMI and RFI, 2) that it is safer than conventional ordnance, and 3) that its fiber optic harness is much lighter than a shielded ordnance wire harness.

The laser ordnance system is sized towards replacing electrically ignited NASA Standard Initiators (NSIs). The system consists of the Laser Standard Initiator, a fiber optic firing harness, and firing electronics, including the high-power laser diodes. Figure 4 shows the system schematically. The system is designed to meet all of the NSI and range safety specifications. The firing electronics are all built to typical spacecraft high reliability standards.

The development effort focused on electrical design and initiator fabrication techniques. The laser diode and fiber optic cable technologies were already mature. The critical design issues for the initiator were consistency of all-fire power levels and in duplicating the explosive output

of the NSI. One important deviation from the NSI design was to manufacture the initiator housing from stainless steel rather than from Inconel, which significantly reduced manufacturing costs. This initiator is being tested to show that it can be qualified to the NSI specification. The ARTS program could not afford to test the large quantities of initiators required to qualify the design to the NSI specification. The electronics are being qualified at this writing to operate at 24 to 32 VDC from -5°C to 45°C.

Flight Experiment

A flight experiment shown in Figure 5 containing all of the ARTS devices is in production and will have completed protoflight acceptance testing by February, 1994. The experiment will then be installed on a host spacecraft and will await launch. The experiment contains a four-channel laser ordnance firing system, two laser standard initiator fired bolt cutters (only two of the laser ordnance channels are used in orbit), two Frangibolts, two Non-Explosive Separation Nuts, and two Fusible Links and their DC to AC power converter. The experiment has eight small preloaded plates that are individually deployed upon release of the ARTS devices. These deployments are verified by hall effect sensors. We used hall effect sensors to evaluate them as a replacement for microswitches. One of each of the two devices will be operated within two months of launch and the second of each of the devices will be operated approximately one year after launch.

The production of a flight experiment proved to be a very useful tool by forcing us to truly complete the development process. All of the issues that effect a component's design and usage from spacecraft interfaces to ground safety to testing and many others had to be successfully addressed. Additionally, staking one's reputation on a device working in space is excellent motivation to dot all the i's and cross all the t's. The dominating requirement for the experiment, other than reliability, was that it pose minimal risk to the host spacecraft. This led to the configuration used wherein all release devices and electronics are packaged inside a common housing, thus protecting the host from any potential mechanical mishap. Another key requirement was the 5 amp current limit set by the host's power bus. Most of the release devices prefer 3 to 4 amps at the low bus voltage of 24 VDC, which can result in a normal current draw exceeding 5 amps at the high bus voltage of 36 V. We had to put a current limiting system in to protect the host at high bus voltages. While this current limit was imposed by designing the experiment around an existing spacecraft, living with it exposed some of the system-level issues that must be dealt with in using these high-current devices. One of the key results of the experiment is to get range safety approval and recognition of the safety benefits of these new systems.

Release Device Comparisons

These new devices are very competitive with one another and with existing components. Pyrotechnically operated devices are presently the most commonly used release mechanisms. The following discussion will compare the components and discuss which tasks are best suited to which devices. This discussion shows that explosively powered devices can and should be replaced for most applications. There are two major divisions in classes of release mechanisms. The first is high versus low release loads. I feel that this is a fuzzy boundary somewhere between 1100 to 4500 N (250 to 1000 lb). The ARTS program targeted the high load release category on the theory that it would be easier to scale down than up. The second major division is whether or not multiple devices must release simultaneously. The following chart exemplifies these divisions.

<u>REQUIREMENTS</u>	<u>OPERATION</u>	<u>COMMON METHOD</u>
High Load, Simultaneous	Spacecraft Release	Pyro Sep Nut
High Load, Non-Simultaneous	Structure Release	Pyro Bolt Cutter
Low Load, Simultaneous	Payload Jettison	Pyro Pin Puller
Low Load, Non-Simultaneous	Solar Array Release	Pyro Pin Puller

There are relatively few types of mechanisms capable of releasing the high loads. There is a larger variety of devices for the lower load applications. The comparison will only compare the ARTS components with the most common devices in use today. Slow devices, typically heat actuated, are usually well suited to the non-simultaneous applications and poorly suited to the simultaneous release applications. These slow devices can sometimes be applicable if an additional release device located in the center of the deployable is operated after all of the load carrying devices have already been released. The faster devices can handle all of the tasks, however, they require higher current than the paraffin release devices and are more complex than the Frangibolts. The pyrotechnic systems in use today are very reliable although they carry the baggage of pyroshock, safety costs, and heavy firing systems.

The ultimate evaluation of a component's worth should be made at the spacecraft-system level. This level is where the elimination of explosives really shines. Of course, all of the devices have to be highly reliable to make the comparison meaningful. The use of laser ordnance is very appealing over conventional ordnance for its reduced weight and safety costs. However the maximum benefit comes from eliminating high pyroshock sources in conjunction with the reduced cost and weight. This analysis leads to the ARTS program approach of eliminating all ordnance possible and firing the remaining ordnance with lasers. These selections also have to take into account factors such as fitting into existing or similar designs, weight versus cost priorities, and other like considerations. The large costs

and weights associated with conventional ordnance make it very unappealing for most new designs.

RELEASE DEVICE	ADVANTAGES	DISADVANTAGES	COMMENT
HIGH AND LOW LOAD APPLICATIONS			
ELEC. PYRO DEVICES • SEPARATION NUTS • EXPLOSIVE BOLTS • BOLT CUTTERS AND PINPULLERS FOR LOW LOADS	• SIMULTANEOUS • PYRO & DEVICE HERITAGE	• HIGH SAFETY COSTS • HIGH FIRING SYSTEM WEIGHT • HIGH PYROSHOCK • MODERATE COMPLEXITY IN MECHANISM	• GOOD TRACK RECORD • ALL SIZES AVAILABLE
LASER PYRO DEVICES • SEPARATION NUTS • EXPLOSIVE BOLTS • BOLT CUTTERS AND PINPULLERS FOR LOW LOADS	• SIMULTANEOUS • DEVICE HERITAGE • REDUCED SYSTEM COST & WEIGHT	• HIGH PYROSHOCK	• EASY TO RETRO-FIT INTO EXISTING SYSTEMS • SIMILAR COMPLEXITY TO ELEX SYSTEMS
FRANGIBOLT	• REDUCED SYSTEM COST & WEIGHT • LOW PYROSHOCK • LOW COMPLEXITY	• NOT SIMULTANEOUS WITHOUT ADD'L DEVICE	• WOULD NEED RESIZING FOR >9000 NEWTONS
FUSIBLE LINK	• REDUCED SYSTEM COST & WEIGHT • LOW PYROSHOCK • SIMULTANEOUS	• MODERATE COMPLEXITY IN FIRING CIRCUIT	• WOULD NEED RESIZING FOR >9000 NEWTONS
NON-EXPLOSIVE SEPARATION NUT	• REDUCED SYSTEM COST & WEIGHT • LOW PYROSHOCK • SIMULTANEOUS	• MODERATE COMPLEXITY IN MECHANISM	• DIRECT REPLACEMENT FOR SEPARATION NUT • WOULD NEED RESIZING FOR >16000 NEWTONS
LOW LOAD APPLICATIONS ONLY			
NON-EXPLOSIVE ACTUATOR-BASED DEVICES • EXCLUDING SEPARATION NUT	• REDUCED SYSTEM COST & WEIGHT • LOW PYROSHOCK • SIMULTANEOUS • NEA IS LOW COMPLEXITY	• MODERATE COMPLEXITY IN SOME OF THE MECHANISMS	• WIDE VARIETY OF DEVICES
PARAFFIN PIN PULLER	• REDUCED SYSTEM COST & WEIGHT • LOW PYROSHOCK	• MODERATE COMPLEXITY IN MECHANISM • NOT SIMULTANEOUS WITHOUT ADD'L DEVICE	• WIDE VARIETY OF DEVICES

Only the Non-Explosive Separation Nut and the Fusible Link are capable of achieving simultaneity without using explosives. The Non-Explosive Separation Nut has more mechanical complexity while the Fusible Link has more electrical complexity. The Frangibolt is the simplest and lightest of the new devices. Laser ordnance is similar in complexity to conventional, electrical ordnance systems but it is much safer and lighter in weight. There is a large variety of non-explosive release mechanisms for the lower load applications so there is very little need to consider explosive devices for these applications.

Future Work

The ARTS program will have future work in working with spacecraft manufacturers and customers to integrate the new devices into space systems. The ARTS program is also hoping to undertake the development of

a non-explosive isolation valve capable of being used on spacecraft carrying large quantities of hazardous liquid propellants. This device would be driven from closed to open upon command, providing a hermetic seal in both states. The valve would have a parent metal seal when in the closed state which is required for safe ground processing. The program would complete a full development and qualification if it is funded.

Conclusions & Recommendations

The benefits of the ARTS components can be maximized by proper application. All explosives that can be eliminated should be eliminated. The remaining explosives should be fired with laser systems. The ARTS devices do not need shielded firing harnesses, so the shielding should be eliminated to maximize weight savings. Safe and arm systems can be reduced to a simple electrical power turn-on connector. Pyroshock testing can be greatly reduced if not eliminated from spacecraft system-level acceptance tests. The shock isolators now used on some spacecraft components can be eliminated.

The ARTS program resulted in several lessons learned. The foremost lesson was that wide voltage swings are very difficult to accommodate for heat-actuated mechanisms. It is important to evaluate requiring the spacecraft electronics to limit this voltage swing somewhat. Producing true flight hardware is a great tool to force thoroughness into the development of components. Testing to the limits of the performance envelope is a very valuable development process to find the strengths and weaknesses of a device. On a specific level, we found that good joint design and installation procedures are important to the reliability of the Frangibolt. We also found that AC heating circuits can be susceptible to inductive losses. The development process and production of the flight experiment verified our assertions that these systems could greatly reduce spacecraft costs when used correctly.

All of the tasks of a spacecraft ordnance system could be performed with a lighter, more economical system utilizing the ARTS-developed components. The implementation philosophy would be to replace all pyrotechnically driven release devices with non-explosive release devices and to fire the remaining ordnance with the laser ordnance system. The primary thrust of the ARTS program has been to create economic savings including the inherent cost savings of weight reductions. These goals have been met with flight hardware being the verification. The ARTS program will conclude with flight-proven spacecraft components ready for implementation on production spacecraft with minor resizing of the components as required. Questions about this program should be directed to William Purdy of the Naval Center for Space Technology in Washington, DC at 202-767-0529.

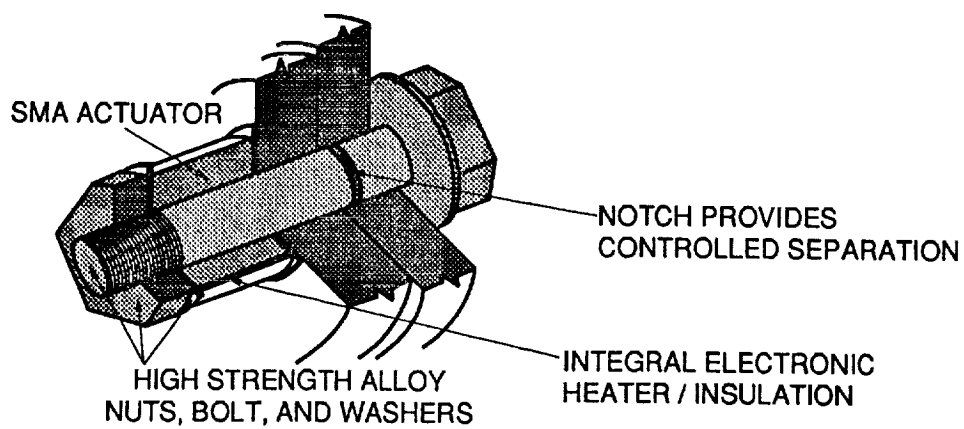
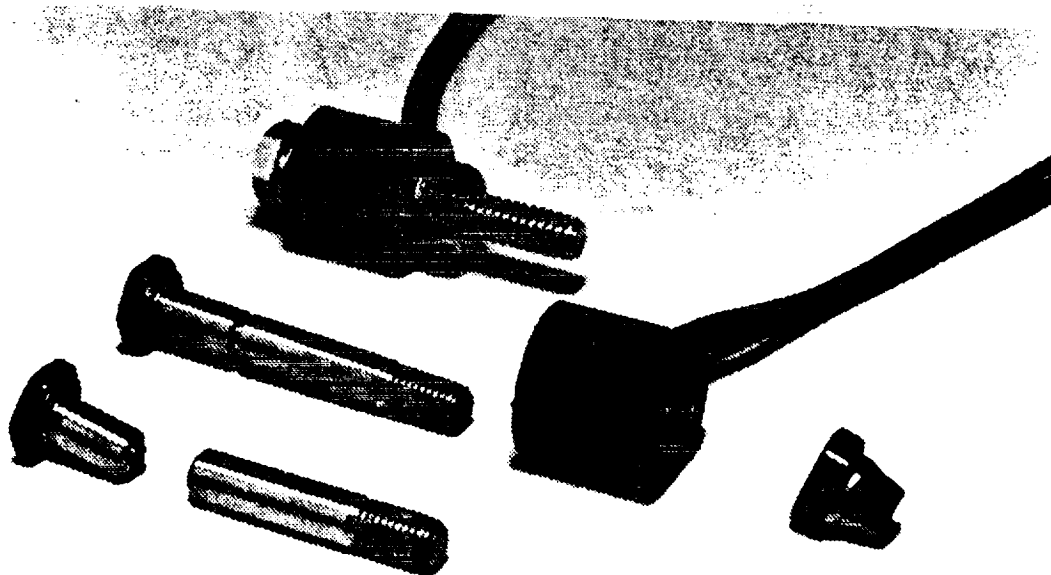


Figure 1: Frangibolt

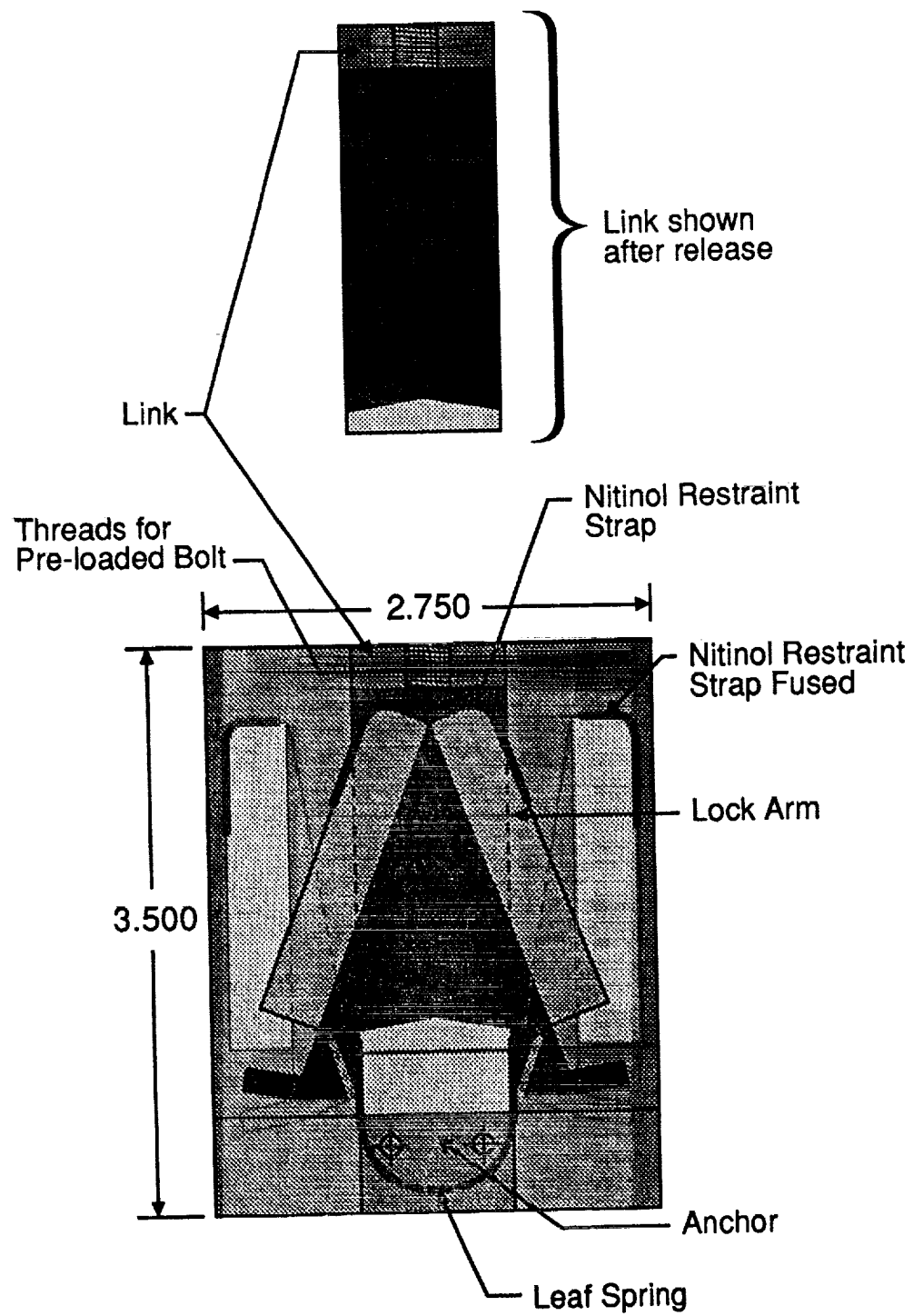


Figure 2: Fusible Link

NONEXPLOSIVE ACTUATOR SPOOL ASSEMBLY

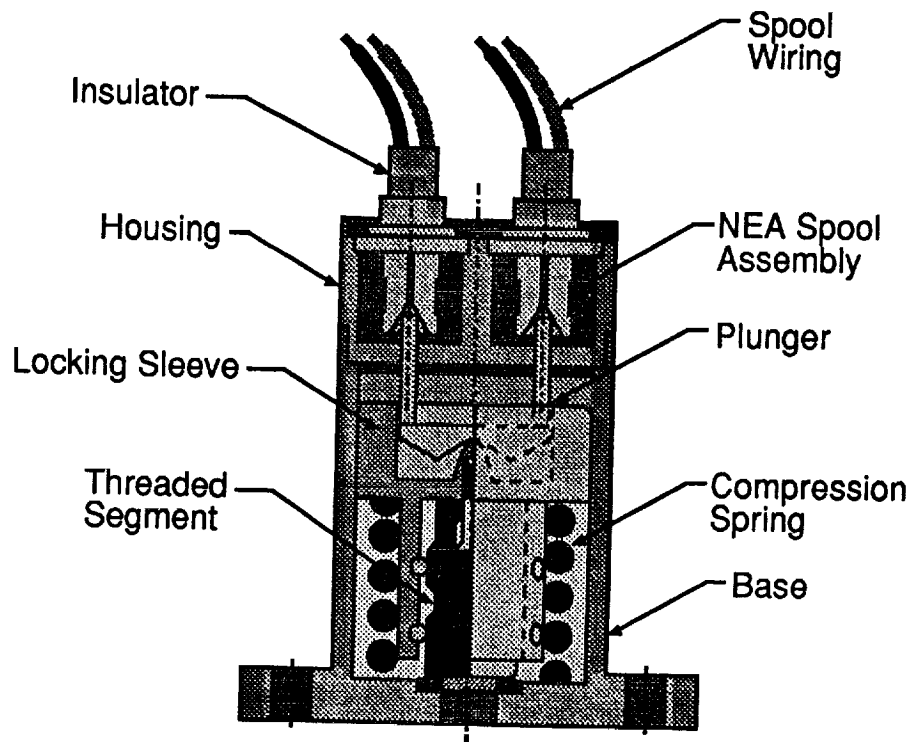
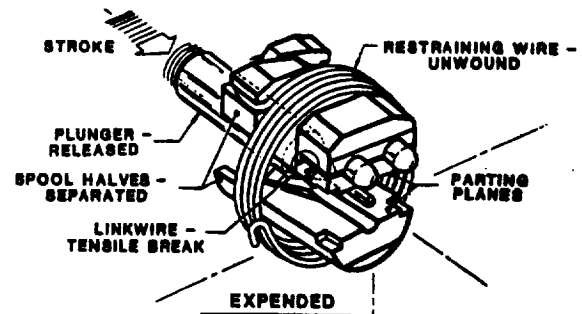
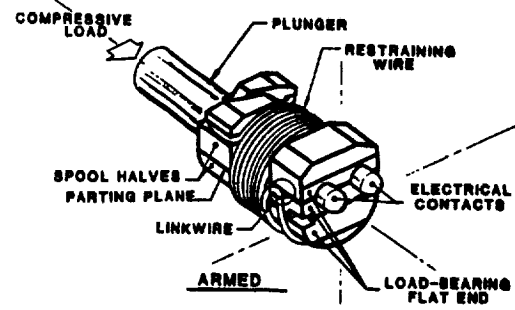
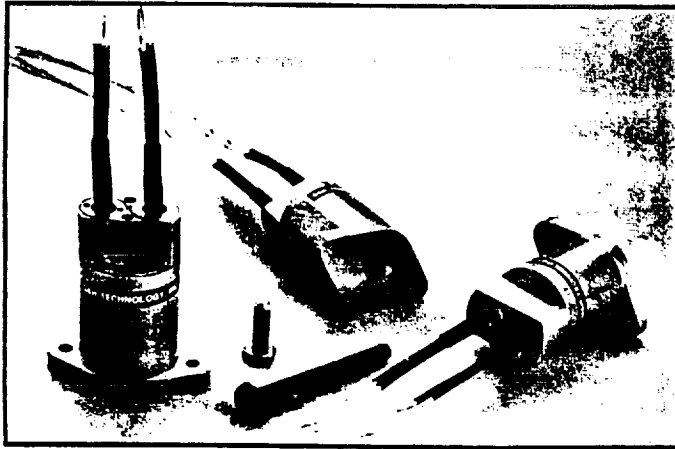


Figure 3: Non-Explosive Separation Nut

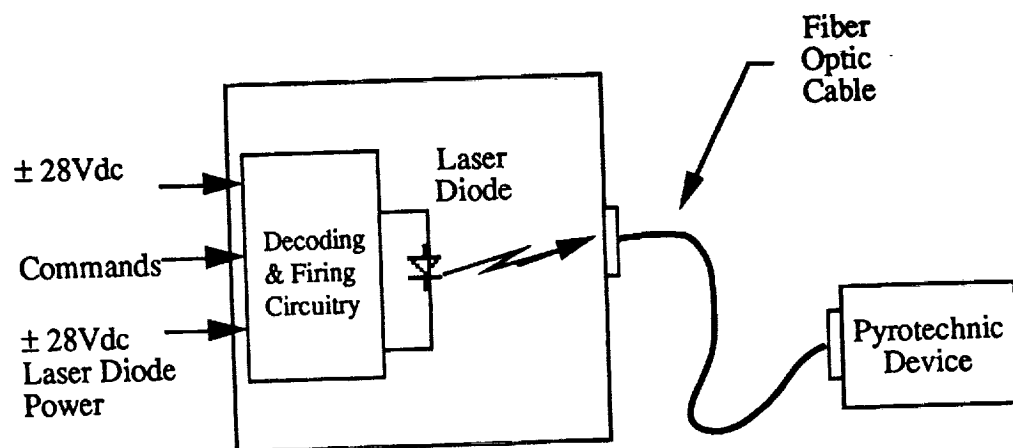
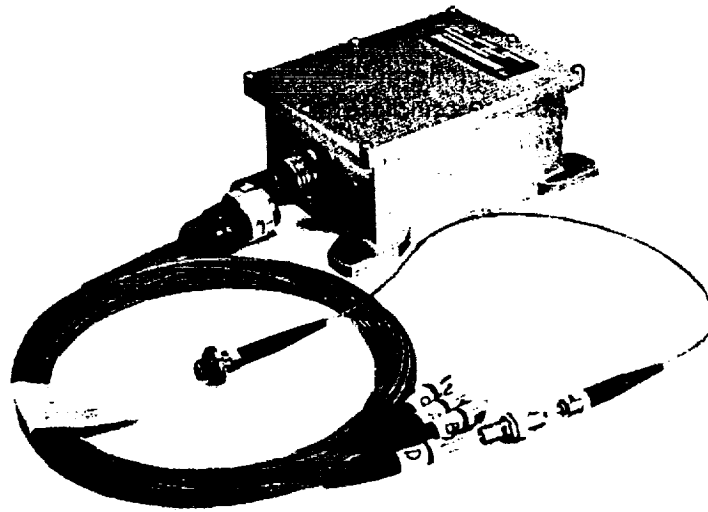


Figure 4 Laser Ordnance System

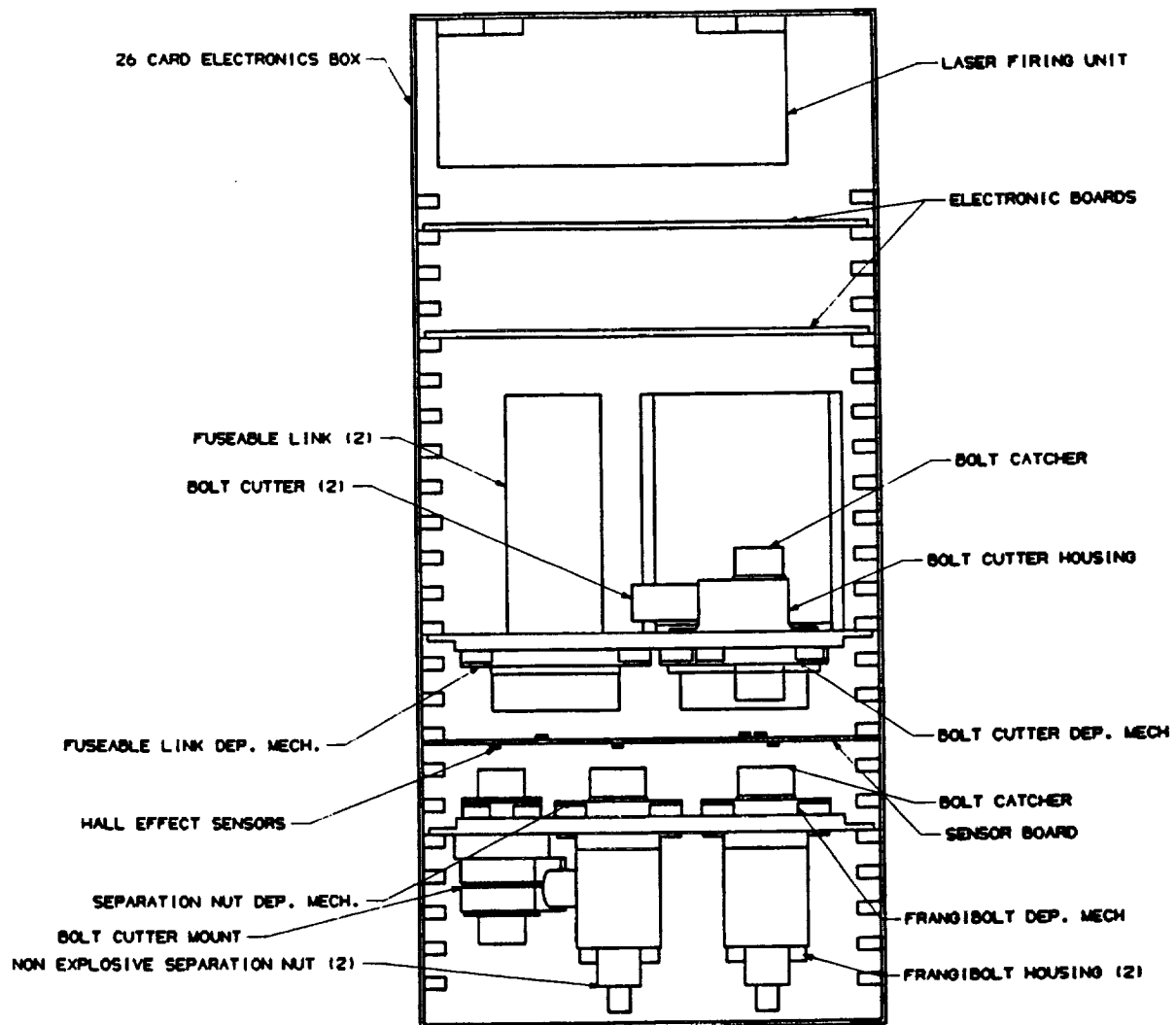


Figure 5 ARTS Flight Experiment

